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Application of ILC Superconducting Cavities for Acceleration of Protons^{*#}

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Beam acceleration in the International Linear Collider (ILC) will be provided by 9-cell 1300 MHz superconducting (SC) cavities. The cavities are designed for effective acceleration of charged particles moving with the speed of light and are operated on π -mode to provide maximum accelerating gradient. Significant R&D effort has been devoted to develop ILC SC technology and its RF system which resulted excellent performance of ILC cavities. Therefore, the proposed 8-GeV proton driver in Fermilab is based on ILC cavities above ~ 1.2 GeV. The efficiency of proton beam acceleration by ILC cavities drops fast for lower velocities and it was proposed to develop squeezed ILC-type (S-ILC) cavities operating at 1300 MHz and designed for $\beta_G=0.81$, geometrical beta, to accelerate protons or H^- from ~ 420 MeV to 1.2 GeV. This paper discusses the possibility of avoiding the development of new $\beta_G=0.81$ cavities by operating ILC cavities on $\frac{8}{9}\pi$ -mode of standing wave oscillations.

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I. INTRODUCTION

Recently, Fermilab proposed to develop an H^- 8-GeV linac, or “proton driver” (PD) [1], with the principal mission to raise the intensity of the Main Injector (MI) to produce so called super-beams for neutrino studies. There are many other possible applications of the PD linac as are discussed in ref. [1,2]. The physics design of the most recent PD version was reported elsewhere [3] and includes the following basic concepts:

- 1) Directly apply SC elliptical 9-cell cavities and klystrons originally developed for the ILC to accelerate protons above 1.2 GeV.
- 2) Develop squeezed ILC-type (S-ILC) cavities operating at 1300 MHz designed for $\beta_G=0.81$ to accelerate protons from ~ 420 MeV to 1.2 GeV.
- 3) To simplify the RF system, it is reasonable and cost-effective to operate the whole linac at no more than two frequencies. Several options are available for the acceleration of protons up to ~ 420 MeV at 325 MHz which is a sub-harmonic of the ILC frequency.

In this paper we present applications of ILC cavities for the acceleration of protons from 600 MeV to 1050 MeV which allows us to avoid the development of S-ILC cavities.

II. PROPERTIES OF ILC CAVITIES OPERATING ON $\frac{8}{9}\pi$ -MODE

The ILC project requires 14560 9-cell SC cavities [4]. Standard ILC RF units consist of three cryomodules with 26 SC cavities and a quadrupole magnet. As noted in the ILC reference design report [4], “the SCRF cavities and cryomodules are the most technically challenging components and require the largest industrial infrastructure and technical ramp up”. The FNAL proton driver requires $\sim 2\%$ of the total number of ILC cavities and cryostats. Industrial pre-production of ILC cavities can provide sufficient amount of cavities for the PD. Therefore it is

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reasonable to provide the largest fraction of the total PD voltage using ILC cryomodules and RF system without extra development.

The ILC cavity consists of 9 essentially identical accelerating cells and therefore have nine normal modes [5,6]. The frequencies of ILC cavity passbands modes are described by the formula [7]:

$$f_q = \frac{f_0}{\sqrt{1 + 2k_{cell} \left[1 + \cos\left(\frac{q\pi}{N}\right) \right]}}, \quad (1)$$

where f_0 is the π -mode frequency, $q=1,2,\dots,N$, N is the total number of cells and $k_{cell}=0.010503$. The latter was fitted to follow the measured frequency spectrum [6]. The measured and calculated frequencies are given in Table 1.

Table 1. Passband frequencies (MHz) of ILC cavities.

q	Mode	Measured frequency	Frequency calculated by formula (1)
9	π	1300.091	1300.091
8	$8\pi/9$	1299.260	1299.268
7	$7\pi/9$	1296.861	1296.908
6	$6\pi/9$	1293.345	1293.317
5	$5\pi/9$	1289.022	1288.952
4	$4\pi/9$	1284.409	1284.355
3	$3\pi/9$	1280.206	1280.080
2	$2\pi/9$	1276.435	1276.627
1	$\pi/9$	1274.387	1274.388

As is seen from Table 1, the frequency of the $\frac{8}{9}\pi$ -mode is just ~800 kHz lower than the operating mode frequency. The axial electric field distribution for passband modes in an elliptical cell cavity can be described by the simplified formula:

$$E_{0,q}(z) = -\sin\left(q\pi \frac{2j(z)-1}{2N}\right) \sin\left(2\pi \frac{z}{\lambda}\right), \quad (2)$$

where $j(z)=1,2,\dots,N$ is the integer step function corresponding to the cell number. The field distributions for three adjacent modes are shown in Fig. 1.

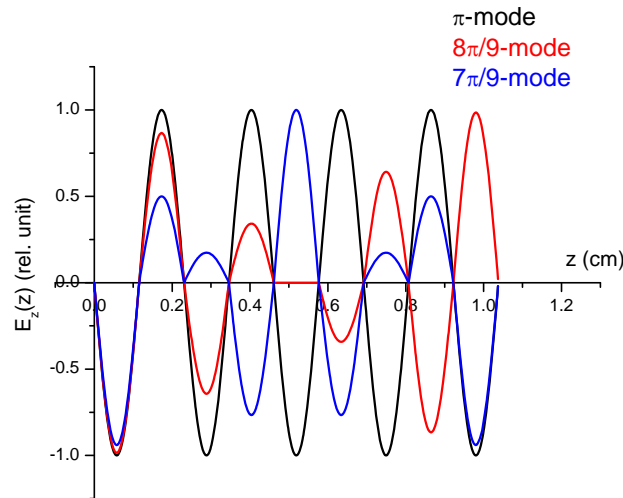


Figure 1: Accelerating field distribution in a 9-cell cavity for π -, $\frac{8}{9}\pi$ -, and $\frac{7}{9}\pi$ -modes correspondingly. The fields are calculated by the simplified formula (2).

Using the formula (2) one can calculate the transit time factor (TTF) for protons. Figure 2 shows TTF calculated for particle velocities from $0.6c$ to the speed of light, c , for three adjacent modes of a 9-cell cavity. The ILC cavities are designed for 31.5 MV/m accelerating field which provides 32.69 MV voltage gain per cavity.

According to the TTF shown in Fig. 2, the acceleration of protons on $\frac{8}{9}\pi$ -mode is possible starting from $\beta \approx 0.8$ providing a voltage gain per cavity in the range of 9 to 14.5 MV. In fact, the $\frac{7}{9}\pi$ -mode can be also used for protons even for lower velocities. However, this mode's frequency is quite far (~ 3 MHz) from the main π -mode's frequency and re-tuning of the cavity cells may require significant deformations before cavity assembly.

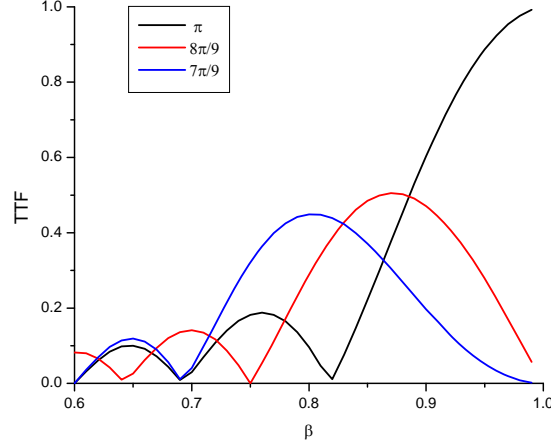


Figure 2: Transit time factor of three adjacent modes as a function of the particle relative velocity.

We have performed 3D computer simulations to define eigenmodes and field distribution on passband modes of an ILC cavity. The major scope of these simulations is to define the peak electric and magnetic surface fields on $\frac{8}{9}\pi$ -mode. The axial electric field distributions on π - and $\frac{8}{9}\pi$ -modes are shown in Fig. 3. The field distribution was converted to the TRACK [8] format for beam dynamics simulations. We assume the same peak surface fields either electric or magnetic, whichever is the highest, on $\frac{8}{9}\pi$ -mode as on π -mode. It appears that a peak surface magnetic field is the highest one and is equal to 1340 G. Figure 4 shows the proton voltage gain in the section of the PD above ~ 150 MeV which contains triple spoke resonators (TSR) with ~ 10 MV/m accelerating gradient and ILC-type cavities. The main parameters of the linac are shown in Table 2. The proposed modifications of the PD

Table 2. Main parameters of the existing and modified PD linac designs.

Parameter	Existing PD design	PD modified for $\frac{8}{9}\pi$ -mode option
Transition energy to ILC frequency (MeV)	420	600
Accelerating gradient in ILC cavities (MV/m)	26.0	31.5
Number of TSRs	42	64
Number of squeezed ILC cavities	63	none
Number of ILC cavities operating at $8\pi/9$ -mode	none	42
Number of ILC cavities	287	263
Total linac length (m)	678	670

parameters with respect to those given in ref. [3] are:

- 1) Increase the number of TSRs from 42 to 66 to push the transition energy from 420 MeV to 600 MeV.

2) Use ILC cavities on $\frac{8}{9}\pi$ -mode in the energy range from 600 MeV to 1050 MeV.

3) Provide a peak surface field of 63 MV/m in ILC cavities of the modified PD design, the same as in the ILC project.

A cavity tuning procedure to implement $\frac{8}{9}\pi$ -mode for proton acceleration in ILC cavities includes the following steps:

- Tuning of cavity cells and a cavity as whole to π -mode's frequency of 1300.8 MHz. Such a tuning may be required for each cell before the cavity assembly because the standard cavity tuner's frequency range is limited to ± 300 kHz [4,5];
- Tuning the frequency of the $\frac{8}{9}\pi$ -mode to be 1300 MHz in the fully loaded cavity at cryogenic temperature.

In addition, some tuning of a coupler and fast tuner may be required for cavities operating on $\frac{8}{9}\pi$ -mode. Specifications to the cavity coupler and fast tuner should be investigated during cavity prototyping.

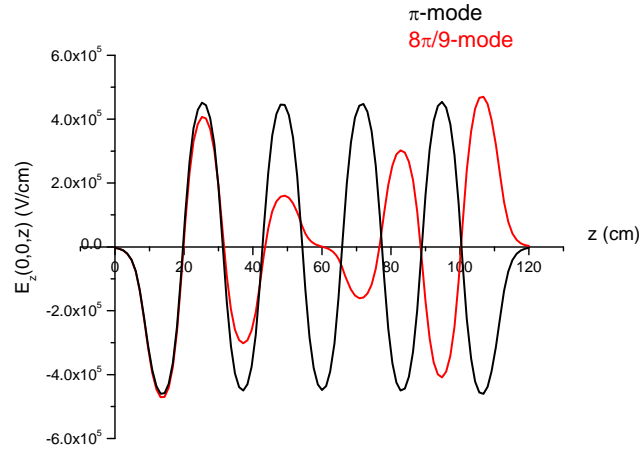


Figure 3: Accelerating field distribution along the ILC cavity operating on π -mode (the black curve) and $\frac{8}{9}\pi$ -mode (the red curve).

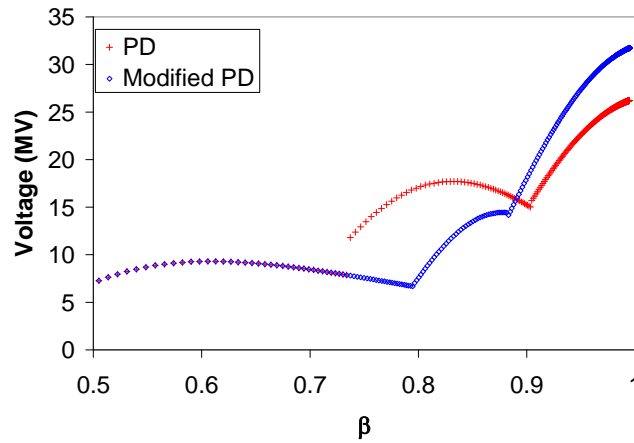


Figure 4: Voltage gain per cavity as a function of particle relative velocity. The red curve corresponds to the existing PD design reported in ref. [3], the blue curve shows the voltage gain in the modified PD with $8\pi/9$ –mode cavities.

III. OPTIMAL TUNING OF CAVITY COUPLERS FOR APPLICATION IN A PROTON LINAC

To minimize the power requirements the waveguide-to-cavity coupling factor, β_C , must be optimized to define cavity loaded quality factor Q_L [9]. In a SC cavity, $Q_L \approx Q_{EXT} \approx Q_0/\beta_C$, where Q_{EXT} and Q_0 are external and intrinsic quality factors respectively. A coupler must be positioned to obtain optimal coupling factor:

$$\beta_{opt} \approx \frac{R_{sh} I_b T \cos \varphi_b}{V_0} \quad \text{which results in } Q_{EXT} \approx \frac{V_0}{R_{sh}/Q_0 I_b T \cos \varphi_b},$$

where $R_{sh} \approx \frac{V_0^2}{P_{diss}}$, V_0 is the highest possible voltage gain of a particle in a cavity, P_{diss} is the RF power dissipated in the cavity, φ_b is the beam synchronous phase, T is the transit time factor (TTF). These parameters for ILC cavity operating both on $8\pi/9$ – and π –modes are listed in Table 3. The synchronous phase in the high energy section of the PD is varied from -26° to 0° . The latter is set for the last 104 cavities (4 RF units).

Table 3. Parameters of ILC cavity for $8\pi/9$ – and π –modes.

Parameter	$8\pi/9$ –mode	π –mode
Optimal velocity providing maximum cavity voltage, β_G	0.88	1.0
V_0 (MV)	14.45	32.69
R_{sh}/Q_0 (Ohm)	409	1036
Peak surface electric field, E_{PEAK} , (MV/m)	60.2	63.0
Peak surface magnetic field, B_{PEAK} (G)	1340	1340

Due to the variation of the cavity effective voltage and beam synchronous phase along the linac, Q_{EXT} has to be varied to provide minimum RF power to each cavity. Figure 5 shows the required Q_{EXT} as a function of the cavity number. Q_{EXT} defines the cavity time constant as is shown in Fig. 6. As is seen from Fig. 5, the Q_{EXT} is varied from $3 \cdot 10^6$ to $9 \cdot 10^6$ which is within the specified range for ILC couplers [5].

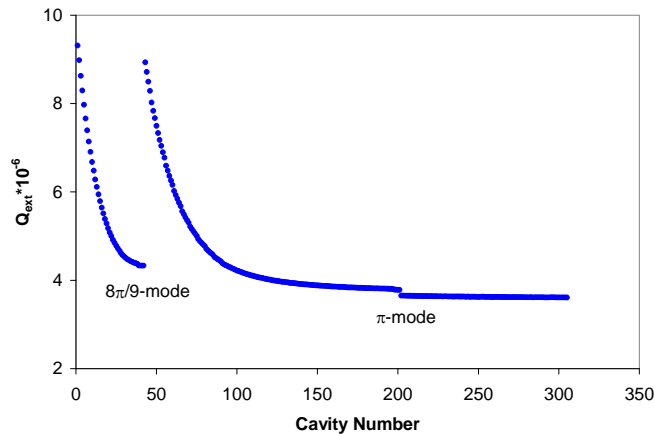


Figure 5: Q_{EXT} as a function of cavity number in the high energy section of the modified PD.

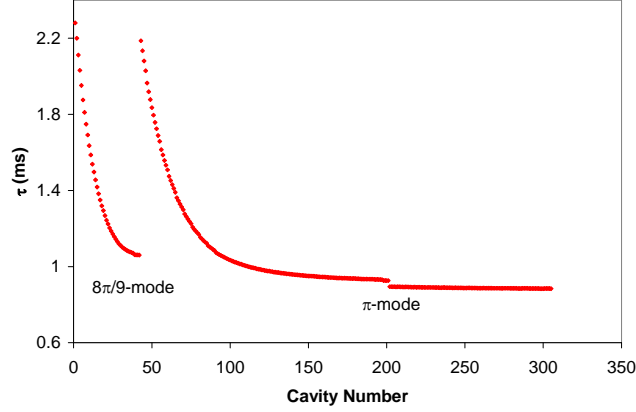


Figure 6: The cavity time constant as a function of cavity number in the high energy section of the modified PD.

IV. CONCLUSION

In the energy range from ~ 600 MeV to 1050 MeV, protons can be accelerated by ILC cavities tuned to operate at 1300 MHz on $8\pi/9$ -mode. The voltage gain per cavity is higher than in TSRs and it is in the range from 9 to 14.5 MV. The advantage of the proposed concept is using ILC cavities down to 600 MeV and avoiding the development of new type of cavities for proton linacs. The complete infrastructure of ILC cryomodules, cavities, focusing quadrupoles and RF system can be applied for the cavities operating on $8\pi/9$ -mode. This concept can be very efficient for multi-GeV proton or H^- machines being considered at FNAL and CERN.

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